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**PULMONARY FUNCTIONS DURING SATURATION-EXCURSION
DIVES BREATHING AIR**

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SUMMARY PAGE

THE PROBLEM

To study lung mechanics in saturation excursion diving.

FINDINGS

The reduction of flow rates produced by pressure increase were compared in acute exposure to pressures of from 100 to 165 feet, and excursion dives were made to the same depths following a 24-hour period of saturation at 35 feet. The pressure-induced reduction in peak flow rates was less after saturation, indicating a partial recovery.

APPLICATIONS

Information obtained in this investigation contributes to further understanding of pulmonary functions under increased ambient pressure. The improvement found in lung mechanics in saturation-excursion diving may contribute to an increase in respiratory capacity at depth and thereby enhance the capacity for useful work.

ADMINISTRATIVE INFORMATION

This investigation was conducted as a part of Bureau of Medicine and Surgery Work Unit MR005.04-0063 - Excursion Dives from the Gas-Saturated State at Depth. It is the first report on this Work Unit. It was approved for publication on 22 August 1967 (Clearance No. 672), sent to Aerospace Medicine and subsequently published in that journal, Vol. 39, No. 3, March 1968. This reprint has been designated as Submarine Medical Research Laboratory Report No. 521, under date of 4 April 1968.

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Pulmonary Functions During Saturation-excursion Dives Breathing Air

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Saturation-excursion dives in compressed air were carried out with 12 subjects in a dry chamber. The diving schedule consisted of (1) 24 hours exposure to 35 feet, (2) one-half to two hour excursion dives to 100-165 feet and (3) stage decompression at 35 feet and at 10 feet, including one hour of breathing pure oxygen prior to reaching the surface. Pulmonary functions were measured at frequent intervals with the flow-volume technique (Wedge spirometer). Data on vital capacity, inspiratory capacity, expiratory reserve volume, tidal volume, and maximum inspiratory and expiratory flow rates obtained during saturation-excursion dives are compared with those collected during acute exposure to increased pressures of equivalent depth. Maximal inspiratory and expiratory flow rates showed a slight increase during the 24-hour saturation period at 35 feet. The subsequent excursion dives reduced the maximal inspiratory flow rates to a significantly lesser degree than during comparative acute exposures to equivalent depths, indicating the development of an adaptation during the 24-hour saturation period.

EXPOSURE to high ambient pressures for short periods of time has been shown to produce an increase in airway resistance, a decrease in expiratory and inspiratory flow rates, and a reduction in maximum breathing capacity.^{2,3,4,7,9,10} These effects of high pressure are thought to be caused by the increased density of the ambient gas.⁹

During prolonged exposure (12 days) to a helium-oxygen-nitrogen gas mixture at 7.0 atmospheres absolute pressure, maximum breathing capacity was found to decrease 38 per cent on the first day of compression and remained at this level throughout the exposure without significant alterations.⁶ Maximum expiratory flow rates (MEFR) were measured at the tenth day of exposure to 7 atmospheres and after recovery. The depression of MEFR found at the tenth day of exposure fell in the range observed during acute exposure to 7 atmospheres. Due to external circumstances, it had not been possible to measure maximal expiratory flow rates (MEFR) regularly during the course of the experiment to obtain information whether some form of adaptation would occur during the 12 days of exposure to high pressures.

As part of a general preparatory program for Sealab II, saturation-excursion dives were performed in a dry chamber using compressed air. The term "saturation diving" applies to diving operations in which divers

are exposed to increased pressures for periods of about 24 hours. This allows all the tissues of the body to saturate fully with the inert gas being breathed. Following the 24-hour saturation period at 35 feet, excursion dives were made from the saturation depth of 35 feet to depths ranging from 105 to 165 feet with subsequent stage decompression. Pulmonary function studies, carried out during these saturation-excursion dives, did provide evidence for the development of adaptation of maximum inspiratory flow rates under these conditions.

METHODS

Saturation-excursion dives—Twelve subjects were exposed to compressed air in a dry chamber, at a pressure equivalent to 35 feet of sea water for 24 hours (33 feet of sea water equals one atmosphere). From this depth, they made "dives" to depths (or pressures) between 100 and 165 feet. These excursion dives varied in duration from 30 minutes to two hours; most were from one and one-half to two hours. A stage decompression, averaging nine hours, was used. The decompression schedules varied slightly, depending upon the depth and duration of the excursion dives.

Surface Dives—The surface dives were made by a rapid compression (75 feet/minute) on air to depths of 109 to 165 feet. Individual subjects were exposed to the same depths to which they had previously descended during the saturation-excursion dives. Flow-volume loops were obtained immediately upon reaching diving depth, and the subject was then returned to the surface as rapidly as Standard Navy Decompression Tables allow. These dives were done at a later time and, due to external circumstances, only four of the previous 12 subjects were able to participate.

Lung volumes and flow rates were determined by the maximal inspiratory-expiratory velocity-volume technique developed by Bartlett.¹ A Wedge Spirometer (Model 370 by Med-Science Electronics), a Tektronic type 502A Dual-Beam Oscilloscope, and a DuMont Oscilloscope camera (Type 53) with a Polaroid film holder were utilized. The bellows component of the spirometer was placed inside the pressure chamber. The six-wire shielded cable, used to connect the bellows to the power supply-amplifier unit, was cut and modified to allow the electrical signal to pass through the chamber wall. The power supply-amplifier unit, the oscilloscope, and the camera were outside the chamber. This type of spirometer, consisting of a bellows and two linear core transducers (one for volume signal, one for flow signal), is ideally suited for high pressure work since its electrical calibration signal is independent of the density and viscosity of the gas being utilized.

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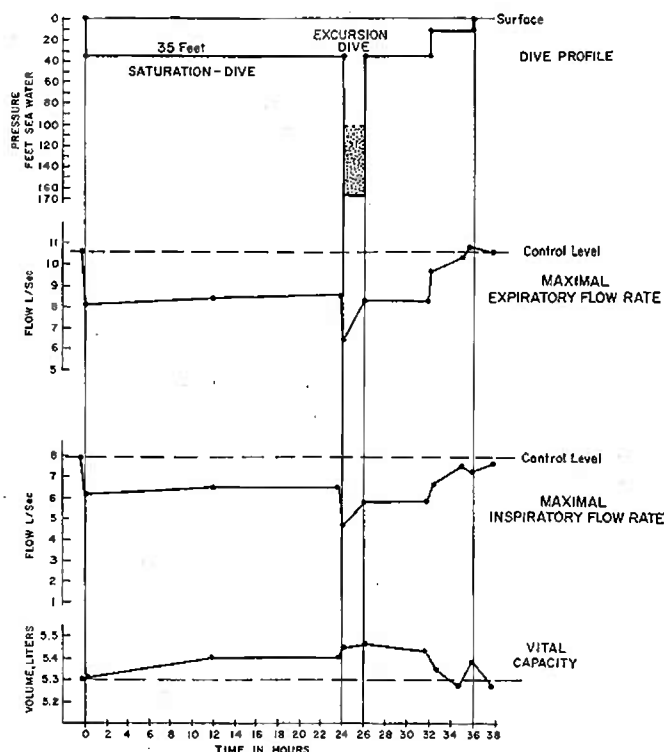


Fig. 1. Saturation-excursion dives. Dive profiles and time course of maximal expiratory flow rate (MEFR), maximal inspiratory flow rate (MIFR), and vital capacity (VC). Mean values of 12 subjects.

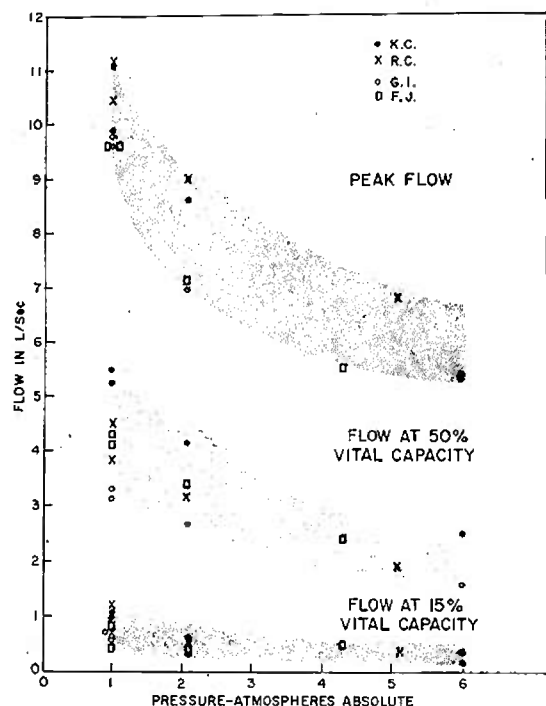


Fig. 2. Surface dives. Changes in peak expiratory flow rate (upper shaded area), flow rate at 50 per cent of the vital capacity (middle shaded area) and flow rate at 15 per cent of the vital capacity (lower shaded area) during compression of four subjects from 1.0 to 6.0 atmospheres in air (Ata). Each point represents the maximal value of two MEFR tracings recorded from each subject at each pressure.

Instructions were given to the subject by use of an intercom.

The subject, while wearing a nose clip, was instructed to commence normal breathing into the spirometer. After the small tidal volume loops began to retrace themselves, one was photographed. This is a modification of Bartlett's technique; he obtained the maximal loop first, then the tidal loop. Instructions to expire completely were given and the camera shutter was opened at the end of expiration; then the subject was told to inspire as rapidly and completely as possible, which was followed by a rapid, complete expiration, with the shutter still open. The result is a photograph showing a tidal loop and a maximal inspiratory-expiratory loop. Vital capacity, tidal volume, inspiratory capacity, expiratory reserve volume, maximal expiratory flow rate (MEFR), and maximal inspiratory flow rate (MIFR) were calculated from the photograph.

RESULTS

Figure 1 shows the time course of pulmonary functions during saturation-excursion diving. The dive profile is depicted in the upper part. The shaded area represents the range of excursions of the various dives (from 100-165 feet), which is followed by a typical decompression schedule.

The MEFR showed the expected decrease from the surface control value (76 per cent of control) immediately after reaching a depth of 35 feet. There was a slight increase of MEFR after 12 hours at 35 feet and a further increase at 24 hours when compared with the initial (0-hour) value. MEFR drops to 60 per cent of control at the beginning of the excursion dive, then returns to control levels during the decompression.

The MIFR showed a similar pattern with an initial decrease to 80 per cent of control at the beginning of the 35-foot saturation dive, followed by the same type of slight recovery after 12 and 24 hours at 35 feet. MIFR decreased to 59 per cent of control at the beginning of excursion dive and began to increase with the decompression phase of the dives but did not quite return to the control level after three hours at the surface.

Vital capacity (VC) increased very slightly during the dive, then began to drop back toward control levels during the later phases of the decompression. The range from high to low points is only 0.2 liters. The largest deviations from control (for the mean values of 12 subjects) ranged from 99.2 to 102.9 per cent of control during 11 sampling times.

The expiratory reserve volume was very slightly decreased and the inspiratory capacity slightly increased during the experiments. The tidal volume was usually higher than control values in most measurements, though changes were erratic.

The slight recovery of the MEFR and MIFR during the 24-hour saturation period suggested that the reduction produced by the subsequent excursion dives might be less than that caused by an acute compression to the same depth. Therefore, surface dives were carried out in which flow-volume loops were obtained at the

surface and at the same depth as the previous excursion dive for a given individual (these were 109, 135, or 165 feet). The flow-volume loops were made immediately after reaching the diving depth. Only four of the twelve divers were able to participate in these comparative surface dives.

Figure 2 shows the reduction in expiratory flow rate, at various lung volumes and various pressures, obtained in acute exposure to high pressure (surface dives). The peak flow rate (i.e., near maximum lung inflation) decreases with increasing pressures. The expiratory flow rate is correspondingly decreased at 50 per cent of VC, and 15 per cent of VC, the latter depends, primarily, on the mechanical properties of the lung.⁵

Figures 3 and 4 give a comparison of MIFR and MEFR in saturation-excursion dives and surface dives. The MIFR, during the saturation-excursion dive, was higher than it was immediately following a direct descent from the surface to an equivalent depth (Figure 3). Figure 4 shows this same type of pattern with the MEFR, but the difference was not as great and, with the limited number of subjects, did not show statistical significance. This recovery, or adaption, was statistically significant in the case of the MIFR (Table I).

DISCUSSION

Adaptive changes in flow rates during saturation diving have not been previously reported. This study provides the first evidence that a 24-hour exposure to twice normal pressure produces adaptive increases in maximal inspiratory flow rate and possibly in maximal expiratory flow rate, so that subsequent excursion dives (ranging in pressures from 4-6 atmospheres absolute) reduce the flow rates to a lesser extent than during comparative surface dives. An explanation for these adaptive changes cannot be given at this time. It is conceivable that the diameter of the airways change or that the respiratory muscles adapt to the increased load of breathing.

The observed improvements of maximal respiratory flow rates during prolonged exposure in a high pressure environment (saturation diving) have a practical significance for prolonged underwater operations, such as Sealab. If the pressure dependent limitation of ventilation is raised, even slightly, it would suggest that the tolerance to exercise might also be improved.

TABLE I. COMPARISON OF REDUCTION IN FLOW RATES PRODUCED BY SURFACE DIVES (A) AND SATURATION-EXCURSION DIVES FOLLOWING 24-HOUR SATURATION AT 35 FEET (B) (CONTROLS = 100 PER CENT, 4 SUBJECTS)

		Maximum Inspiratory Flow Rate (MIFR)		Maximum Expiratory Flow Rate (MEFR)	
		A. Surface Dives	B. Sat-Exc. Dives	A. Surface Dives	B. Sat-Exc. Dives
Depth	Mean	79.5%	82.6%	78.7%	79.2%
35 Feet	S.D.	±10.5	±5.8	±8.9	±4.1
109-165 Feet	Mean	47.7%	60.9%*	57.1%	60.5%
	S.D.	±6.5	+7.3	±3.2	±3.1

*Flow rates under conditions A and B statistically significantly different at the 5% level.

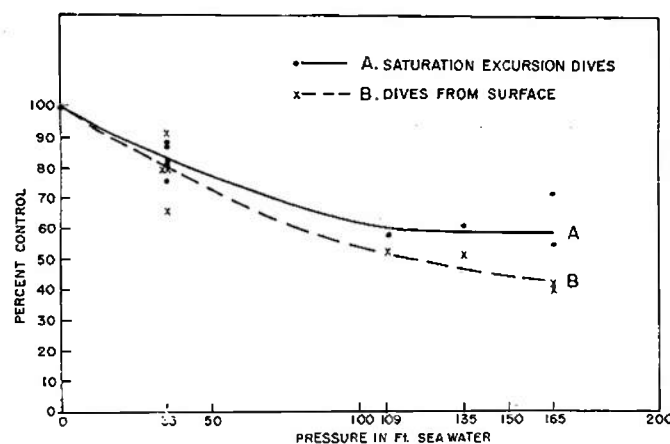


Fig. 3. Effects of increased pressure (dives) on maximal inspiratory flow rate (MIFR). A. Data obtained after 24-hour saturation at 35 feet and excursion dives to 109, 135, and 165 feet, following saturation at 35 feet (·). B. Data collected on the same subjects during compression from surface to 35 feet and to 109, 135, and 165 feet (x). Four subjects.

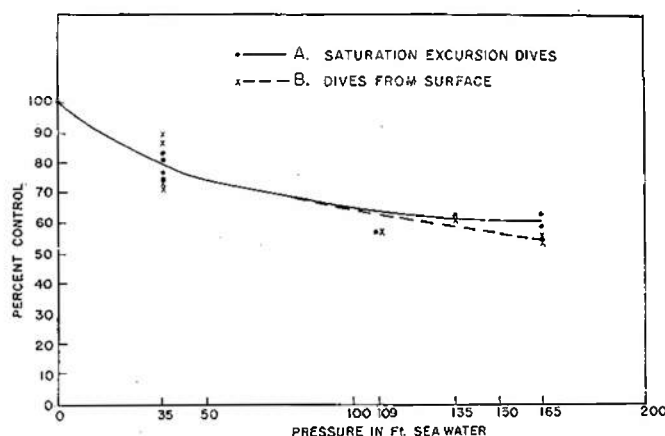


Fig. 4. Effects of increased pressure (dives) on maximal expiratory flow rate (MEFR). A. Data obtained after 24-hour saturation at 35 feet, and excursion dives to 109, 135, and 165 feet, following 24-hour saturation at 35 feet (·). B. Data collected on the same subjects during compression from the surface to 35 feet, and to 109, 135, and 165 feet (x). Four subjects.

The small increase in VC, observed in the saturation-excursion dives with compressed air, is in agreement with findings of Hamilton, et al.³ during saturation-excursion diving to 650 feet using a helium-oxygen breathing mixture. However, data obtained during a 12-day exposure to helium-oxygen at 7 atmospheres (200 feet) showed a 23 per cent decrease in VC during the first day and returned to control values after four days of exposure. In Sealab II, Mazzone⁸ reported a 14 per cent decrease in VC at 207 feet. The values varied from day to day, were more depressed during the mid-portion of the run, and showed some return to control values during the second week.

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13. ABSTRACT <p>Divers work at increased pressures and this results in increased gas densities for a given breathing mixture. The increased density causes an increase in the work of breathing and consequently reduces the maximum ventilation possible during exertion, a condition which sets the limit for useful work at depth.</p> <p>As a part of the general preparatory program for the SEALAB II project, lung function tests were performed on divers during saturation-excursion dives, and also during surface dives ("bottom-drops") in a dry chamber. The saturation-excursion dives consisted of a 24-hour saturation exposure at 35 feet and excursions from this depth to depths varying from 105-165 feet. Maximal inspiratory and expiratory flow rates are two functions which show a depth-dependent reduction during diving. The findings in these studies indicate that after a 24-hour saturation period at depths, adaptation had taken place which resulted in an improvement in flow rates. The subsequent excursion dives reduced the maximal inspiratory flow rates to a significantly lesser degree than during comparative acute exposures to equivalent depths. It is hoped that the time course of maximal flow rate can be established during prolonged exposure to high pressures in SEALAB III. There would be a high probability that the predicted improvement in flow rates would be associated with a higher level for useful work at depth.</p>			

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